VEHICLE FOR DISABLED PERSONS WITH THE POSSIBILITY OF OVERCOMING THE STAIRS

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Abstract

Statistics estimates that in the today world 28 million people are depending on technical aids in the movement. It is estimated that each 250th person need wheelchair. The most of these people are still able and want to work, rather than be a burden to the community. However, our world is built for us, "normal" people, who think they will forever be able to move it.

The report for the Republic of Croatia states that the Croatia is home to nearly 150.000 people with damage of the musculoskeletal system, and many of them for their movement need technical aids. Every year the number of people with paraplegia and quadriplegia increase by about 100. Wheelchair for move around the flat ground is technically simply to solve. However, our world is full of obstacles that are insuperable for standard wheelchair, and perhaps the most serious obstacles are stairs.

In the year 2010, Croatian company KOPACK, which is primarily engaged in the production of packaging machinery, started the development of motorized wheelchair with the possibility of overcoming the stairs (climb/descend). A key element in the system of climbing and innovative difference from other solutions is so called the climber. The cooperation on the project with the Faculty of Mechanical Engineering University of Zagreb starts at the beginning of the 2011. KOPACK concentrated his work on the mechanical part of the structure, and the Faculty on the control part of the problem. So far initial model was successfully tested. Further work is on the development of more advanced versions.

1. INTRODUCTION

Production of motorized wheelchair to move across flat terrain has long been the world's good business. There are a number of manufacturers, different categories usually similar configurations. Rates generally range from $ 1.500 to $ 4.000 [1], depending on the characteristics of the vehicle (speed, range, turning radius, capacity, etc.). The progress and the availability of cheap electronics made it possible to add some parts and improve classic motorized wheel vehicle to something that will allow overcoming the stairs. According to the static, stability of the vehicle while climbing or descending the stairs, solutions may be divided into two categories: static stable and static unstable vehicles.

Static stable vehicles have characteristics that power failure will remain the vehicle in place, therefore the security aspect is very reliable. This kind of vehicles are usually designed that the lower part of the vehicle have caterpillar-like tracks. During the driving in the flat terrain that part is retracted. Reaching the stairs wheels are raised, and the caterpillar-like tracks is activated. Climbing or descending the stairs is now replaced with driving on a slope, Figure 1. Examples of such solutions can be seen in [2] and [3]. Climbing and descending is performed so that a driving person always sits with his back to the stairs. This provides better static stability of the vehicle during the mastering stairs. The length of the caterpillars is limited by the length of the vehicle. To further increase the stability some models have the ability to draw additional telescopic wheel-supports. Tracks are made of rubber as not to damage the edges of the stairs. If such a model come out from the laboratory and become a product minimum price is around $ 10.000.

Static unstable vehicles are much more attractive and more sophisticated but also more expensive. They use the principle of driving on two wheels (as Segway). Some examples can be seen in [4] and [5]. Perhaps the most famous representative of this type of vehicle is iBot that was conceived by Dean Kamen, and can be seen in Figure 2. Although these vehicle is declared for mastering the stairs it is almost impossible to find recordings that confirm this. On some recording of climbing it is possible to see a man as an assistant. Probably the main reason is static instability of the vehicle. In the event of a power failure, malfunction or some mistakes, the outcome can be fatal for a person sitting in the vehicle. Rolling over the stairs is possible, and as the vehicle weight may reach 100 kg and more, it can lead to death. iBot began selling in 1999 and had great media attention. Already in 2009 company stopped the production and sale with the unofficial explanation that the production is unprofitable (in development was spent 50 million US dollars) since the annual level not sell enough pieces. Price for one vehicle was $ 25.000, which is the rank of the middle class car. Probably there were accidents that resulted in claims for compensation, which is certainly contributed to the decision on the termination of production. In 2016 it was announced that the development and production of the iBot continues under the sponsorships of the Toyota.

Figure 1. Caterpillar-like vehicle

Figure 2. iBoot vehicle

The literature may find some other "exotic" solutions, as can be seen in [6], but it currently is not out of the lab and cannot be purchased. Also, an interesting solution can be seen in [7], that combines static properties of stable and unstable vehicle type, but there is no information that the idea was realized and tested.

3. KOPACK WHEELCHAIR

Kopack vehicle for disabled persons belongs to the category of a static stable vehicle which ensures a high degree of safety in case of failure or power failure. The vehicle is four wheel driven by a DC motors, with separate actuators on left and right side of the vehicle. The vehicle can be set on the auxiliary (free) wheel, which facilitates the driving of the indoor areas and decrease the force required for rotation. The user controls the vehicle through the joystick. On the vehicle console with display user can choose drive modes and parameters of the driving process. The weight of the empty vehicle is around 80 kg.

A key element of which this vehicle achieves stairs climb/descend is called climber. The climber is curved mechanism actuated with an additional motor that moves climber levers. During the climbing or descending the chair and the driver remain in a horizontal position. Climbing operation is partly performed automatically, and partly under the control of the operator (command for the next step). Maximum slope which the vehicle can overcome is 37°. Figure 3 shows a side view of the vehicle, while Figure 4 shows descend the stairs. Video display of climb and descend can be seen at [8].

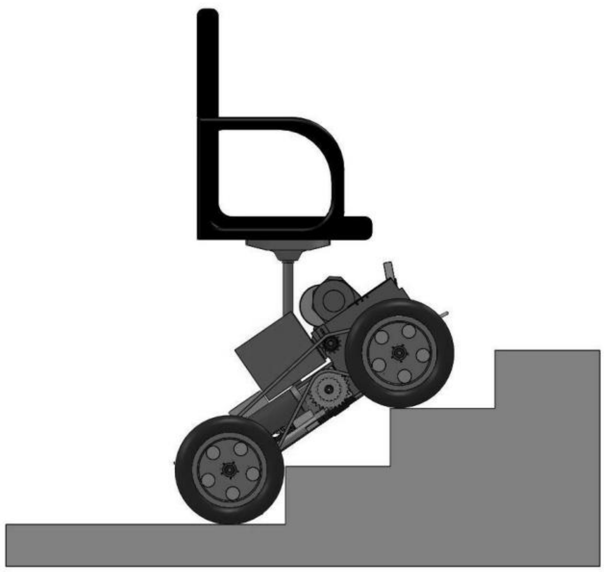

Figure 3. Side view of the Kopack vehicle

As this is an experimental vehicle it is important to have the ability to track all the variables of the process to notice details that the eye cannot distinguish. Therefore, the control computer of the vehicle is wireless connected (Bluetooth) to a personal computer. With the supervisor program it is possible to monitor and record vehicle kinematics and other parameters of the driving process. Also, the vehicle can be operated remotely, without the presence of the operator in the seat of the vehicle. The vehicle driving is intuitive and with a little practice can be learn quickly.

Figure 4. Stairs descent

4. MECHANICAL SYSTEM DESCRIPTION

Vehicle have two drive wheels on each side. Each pair of wheels is driven by DC motor on 24 V. Wheels diameter is 300 mm, distance between front and rare wheels is 530 mm and distance between left and right wheels is 680 mm. The larger wheelbase contribute to a better vehicle stability on the stairs, but could be a problem with a vehicles "stranding" by the central portion when the climbing ends or descending begin. The smaller wheelbase would prevent stranding, but would also reduce the stability of the vehicle on stairs. Wheels distance across the width is determined by the requirements of the construction (drives, batteries, chair width, etc.).

Each side of the vehicle is driven by one INVACARE DC motor of 220 W with built-in brake and gearbox. Transmission of motion and torque is achieved from the motor to wheels through the chain on each side. In this way, all wheels of the drive are power wheels and are speed synchronized. There are also extra wheels at the rear that can be lowered and raised. Their basic function is to reduce the necessary force when driving, especially when turning.

According of the vehicle design it is possible to make a connection between the speed of the wheels (ω_R , ω_L) and speed of the vehicle in the external coordinates (translation v and rotation ω)

$$v\ \% = \frac{1}{2}(\omega_R + \omega_L)$$
$$\omega\ \% = \frac{1}{2}(\omega_R - \omega_L)$$

All speeds are expressed in percentage of maximum which is suitable for control algorithm.

The central part of the vehicle, which allows vehicle physically overcome the stairs, is climber shown in Figure 5. It is curved mechanism with three levers, which serves as a support to the stairway and lift or lower the vehicle. Climber is generally moving in one direction, and its speed of rotation determines the rate of climb/descend. When the curved mechanism rotate levers move in or out, depend of rotation angle. If levers must support a vehicle on stairs then it is out, otherwise it moves back preventing to scrape a floor. Climber unit is driven by DC motor with a large gear ratio to ensure the self locking mechanism.

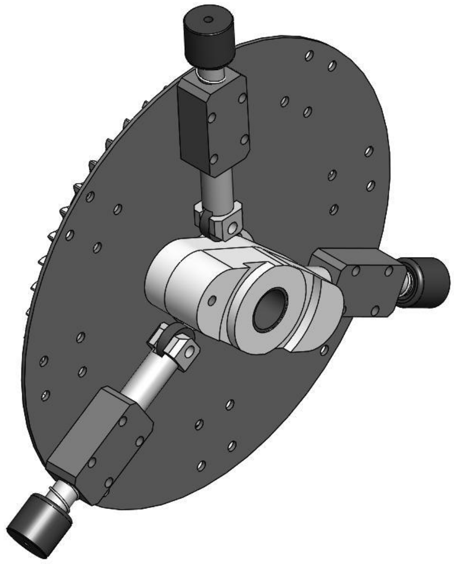

Figure 5. Climber mechanism

During the climb/descend vehicle chair must always remain in the horizontal position. Therefore, another drive with DC motor is added. The range of the chair movement determines the maximum slope that the vehicle can be overcome, and it is 37°. Position of all vehicle drives can be seen in Figure 6.

5. CONTROL SYSTEM DESCRIPTION

Control system of the vehicle is divided into two parts. The host computer is on the vehicle and manages all resources of the vehicle to the embedded hardware. On the host computer via a serial line so-called terminal unit is connected, which sends commands to vehicle. The terminal can be any computer that can communicate via a serial line and has built in the protocol communication, but does not have to know the vehicles hardware.

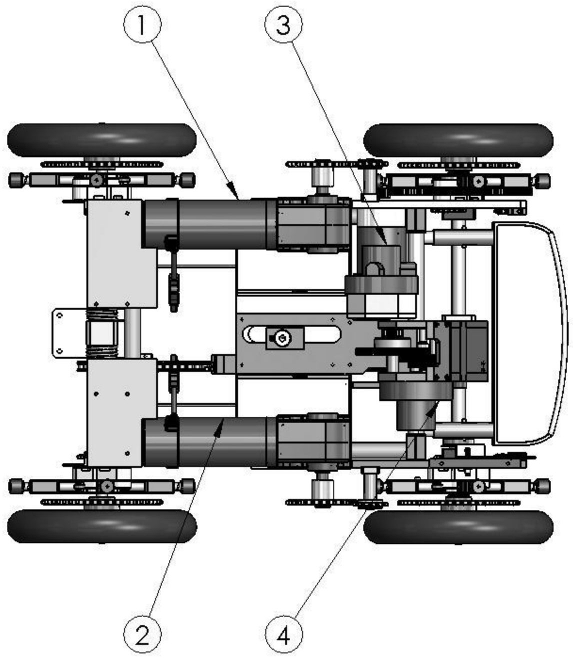

Figure 6. Vehicle cross-section from above (1) left drive, (2) right drive, (3) chair drive, (4) climber drive

For vehicle mainframe Atmel microcontroller AT89C51RE2 with two serial communications is selected. One communication is used for communication with the terminal unit, and the other communication is for auxiliary processor. The auxiliary processor is simple AT89C4051 because mainframe computer has not enough input/output lines. The auxiliary unit process signals from encoder and digital sensors.

Motors are controlled by pulse width modulation (PWM) and over the line that determines the direction of rotation. Each motor has a brake which takes approximately 0.3 seconds to change the state (on/off). If the vehicle is stopped more than 5 seconds, wheel motors themselves braked automatically. The wheel motors have incremental encoder with 2000 pulses per revolution, and are used to measure the wheel speed. The wheel speed is controlled by modified PI controller every 100 ms. The terminal unit sets the vehicle translational and rotational speed. Then the required speeds of the left and right wheels are calculated according to the kinematic model of the vehicle.

Position of the climbing lever is also measured by incremental encoder and its reference position is determined by an inductive sensor. When the lever rotates for a one third of circle, encoder count to 866 impulses, which means that the resolution of the lever position is about 1/7 degree. At 50% rotation speed rate lever takes about 6 seconds for 1/3 circle rotation. Due to the large transmission ratio a climbing speed feedback is not necessary, therefore the lever position control is relatively simple.

When driving on flat terrain vehicle chair inclination remains unchanged, and can be pre-set according to each person. This pre-set chair inclination is activated automatically when on the terminal device is selected a mode that is not climbing or descending. When vehicle is climbing or descending there are at least two reasons why it is necessary to control the horizontal state of the chair. The first reason is comfort of the driving person, but far more important is the stability of the vehicle, i.e. preventing vehicle rollover. The chair position is continuously measured by a potentiometer and specific position is checked with inductive sensor. To control the chair inclination it is also necessary to measure absolute tilt angle of the vehicle from the horizontal plane which is done with the SCA61T inclinometer. However, as the tilt sensor is in fact converted accelerometer for measuring inclination, it also measures a dynamic component of vehicle movement. Therefore the measured signal must be filtered in order to obtain useful information for the chair tilt controller.

Before the vehicle start to climb it is necessary to approach the stairs with front vehicle side to no more than twenty centimeters. Then entering the climbing mode, chair tilt will adjust automatically (slightly ahead due to stability), and the lever takes a starting position for climbing, video [8]. All time while the vehicle is in the climbing mode wheels gently pull the vehicle forward by a constant force approximately 15% of the maximum (speed control is off), and vehicle moving in the back is not possible. This provides a sense of safety. When the user determines that the vehicle front or back wheels touch next stair (at that moment the climbing lever should be above that stair) he or she can press the button (arrow forward) to require climbing to the next step. Then climbing levers starts to rotate by set speed (can be changed in terminal unit), and also wheels rotate to assist climbing. Torque on the wheels depends on the stage of overcoming the stair, and is determined by the angle of climbing lever, Figure 7. At the first moment wheel torque is small, but when levers sufficiently raise the vehicle torque increase to help the climbing lever. In the final phase of overcoming stairs torque on the wheel again decreases preventing the vehicle to hit a next stair with high speed. During the climbing lever rotation, the vehicle is lifted to the next step, and chair with a small deviation remains in a horizontal position.

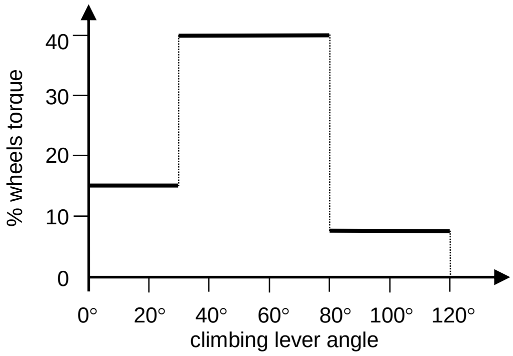

Figure 7. Wheel torque vs. climbing lever angle in one climbing step

When the control system receives information that the vehicle is horizontal (at the end of climbing), wheels do not pull forward and there is no danger of uncontrolled movement. If during a climbing a man notice that this force ahead may be dangerous, still it can be turned off by pulling the joystick in the back. In this way a man increase the feeling of the vehicle control.

Similar actions takes a place in descending vehicles down the stairs. The essential difference is that in the case of descending the movement of the vehicle and the gravity are of the same direction, therefore the process is less stable. In addition there is a psychological barrier when the vehicle wheels moves closer to the edge of the stairs. Then the vehicle must be moved a little forward to rely on climbing levers. With ordinary wheelchair vehicle that would mean a fall down the stairs, but with this special wheelchair we come to a safe position for lowering and nowhere do not fall. All the time during the descend, vehicle wheels run slowly to back contributing the feel that we are "glued" to stairs. When we want to get to the next step joystick sensitivity is reduced considerably and does not allow setting a high speed.

The control console of the vehicle is shown in the Figure 8. It consists of joystick, four buttons (MENU, ENTER, 🡩, 🡫) and an LCD with four rows of 20 characters, which allows communication with the user. As a user would not have to constantly look at the display, the console has little speaker for drawing attention to themselves. Pressing the MENU button enters the system menu where you can choose the driving mode and some parameters of the drive. All parameters are retained even after power shutdown.

Console menu is organized on three levels. The first menu level (Menu A) is the one that users need and use the most often. At that level user selects driving type and entries no parameters. Selecting the service mode user can test the individual components of the vehicle and check their correct operation. For a service work it is necessary to know the technical details of the vehicle. Entering the settings mode user can change vehicle characteristics which influences the behavior of the vehicle. The characteristics of the vehicle should be changed only by responsible person. In the case that you make some random changes all the vehicle settings can always be restore by selecting "Factory settings" from Menu B.

Figure 8. Control console with joystick and user interface

User menus are as follows:

Menu A: Indoor drive
Outdoor drive
Climbing
Descending
Rotation
Service mod → *Menu B*

Menu B: Info
Left motor
Right motor
Chair motor
Climbing motor
Test joystick
Test sensors
Settings → *Menu C*
Factory settings
Remote control
Reset EEPROM

Menu C: Chair zero
Indoor – forward
Indoor – backward
Indoor – rotation
Outdoor – forward

Outdoor – backward
Outdoor – rotation
Rotation speed
Brake time
Climbing threshold
Threshold speed
Climbing speed
Descending speed
Acceleration
Control type

The driving console sets command to the main vehicle computer via serial communication (TTL signal level) in the following format:
NN aa bb CS /
where character # indicates command begin, / indicates command string end, NN is the command number, while the aa and bb are command arguments. CS stands for Check Sum and serves as a check on the receiver whether the command is correctly transferred. All arguments are transferred in the hex format, and negative values are recorded as a second complement. Table 1 shows some examples of commands.

Table 1 Commands to the main vehicle computer

NN	aa bb	Command
2	vv rr	Set translation speed of the vehicle on *vv* and rotation speed on the *rr*, in%.
4	aa xx	Set PWM of climbing motor on *aa*, in %.
5	aa xx	Set PWM of chair motor on *aa*, in %.
7	aa tt	Set climber forward with PWM on *aa* to climber sensor, but no more than *tt/10* seconds. At the end leave motor brake off.
10	aa bb	Turn chair inclination controller off/on (00/01). If on, set inclination on *bb*°.
16	aa xx	Set all breaks time on *aa/10* seconds.
20	xx xx	Set current chair position as horizontal (zero) position.
99	xx xx	Show internal variables.

xx – don't care

This means that the vehicle can be operate by any device that can communicate and can create adequate command set.

It is important (especially in the vehicle testing phase) to monitor vehicle parameters in real time. Therefore the Bluetooth telemetry is built in the system. There are 18 variables that can be monitored during the vehicle movement. Some of them are:

- the translation and the rotation speed of the vehicle measured by incremental encoders (Equation 1)
- each wheel speed
- vehicle tilt and chair position
- PWM signal to all motors
- status of digital sensors and motors brake
- climbing levers position
- battery status

Vehicle variables are sent to console at intervals of 100 ms. Console receives data, and at the same time sent them to the Bluetooth. Personal computer receives data, display them and store for further analysis. Figure 9 shows the typical telemetry data at descending one stair.

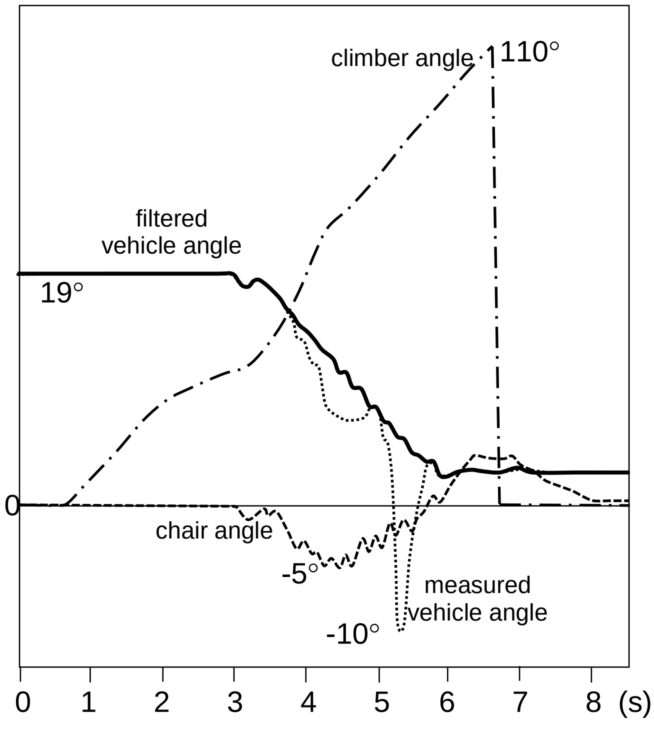

Figure 9. Telemetry data in descending one stair

The dot line shows the vehicle inclination measured by inclinometer (actually accelerometer) and the bold line shows the estimated (filtered) vehicle angle that control the inclination of the chair. The rapid drop of the measured inclination signal (after 5th second) and then return was caused by an impact of the vehicle to the next stair, not a real vehicle angle. Estimator prevents such false information entered into the control system and the chair jerk.

6. CONCLUSION

Although in Croatia there are a lot of persons with locomotors disabilities, their problem is not given sufficient attention. The solution to this problem is very complex, and the financial status of such persons (often unemployed) is usually not good. Therefore, there is no greater investment of companies because no one expect big profit. The community sympathizes with their problems, but nobody want to invest in the technical solution of the problem. Such was the fate of this project. He was rejected by the Croatian Science Foundation with the unofficial words "Who need it?", and with a decent formal explanation. Of course, this vehicle should be used by someone else. We will forever remain young and healthy.

Fortunately there are people to whom the material is not in the first place. These people are taking their time, resources, knowledge, perseverance and love to help others. The result is such a vehicle that needs more work to become public operable. However past experience in the design and control the wheelchair gave us a lot of valuable experience in dealing with this problem. The third version of the vehicle is under construction and we hope it will be successfully tested by some disabled person.

7. REFERENCES

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